NASA ESTO Instrument Incubator Program
Cryospheric Advanced Sensor

A Combined Spatial- and Frequency-Domain Interferometer for Sea Ice Thickness Measurement

[1]Ziad A. Hussein, Principal Investigator
Ben Holt, Kyle McDonald, Rolando Jordan
, John Huang, Anhua Chu, Kyung Pak, Mike Gradziel
[2]Yasuo Kuga, Akira Ishimaru, Sermsak Jaruwatanadilok,
[3]Prasad Gogineni, Torry Akins, Brandon Heavey
[4]Don Perovich, Matthew Sturm

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[2]University of Washington, Department of Electrical Engineering, Seattle, WA
[3]University of Kansas, Department of Electrical Engineering, Lawrence, KA 66045
[4]US-Army Cold Region Research and Engineering Laboratory, Hanover, NH

Outline

- Goals and Objectives
- Science Motivation & Background
- Sea-ice Sensing Model for VHF
  - Forward model for sea ice
    - 2-D Small perturbation method
    - Volume scattering based on Rayleigh approximation
  - Inverse problem for sea ice thickness estimation
    - Genetic algorithm (GA)
    - Gradient descent (GD)
    - Least square (LSQ)
- Prototype Instrument Technology
  - Instrument design and development
    - Radar design
    - Antenna design, RF and digital, & Mechanical hardware design configuration
  - Verification with measured data from controlled laboratory experiments
  - Field experiment validation
- Summary

Ultimate Goals and Objectives:

- Development of reliable technique(s) for direct estimation of sea-ice thickness, and associated field experimental instrument including a demonstration of the instrument capabilities through a sea ice field experiment conducted on the Arctic Ocean ice cover.

- Development of technology to support a future cryospheric spaceborne mission, that will combine the frequencies required to determine both sea ice thickness and snow cover characteristics.

A Combined Spatial- and Frequency-Domain Interferometer for Sea Ice Thickness Measurement

Science Overview

NASA ESE Question: ***What changes are occurring in the mass of the Earth's (sea)ice cover?***

Role of Sea Ice and Snow in Climate

- Ice cover regulates heat exchange between ocean and atmosphere.
- Ice impacts ocean circulation
  - ->Growth releases brine which increases ocean density.
  - ->Surface meltwater influences thermohaline convection.
- Ice and snow play key role in Earth's surface albedo budget.

Preliminary Sea Ice Thickness Measurement Goals

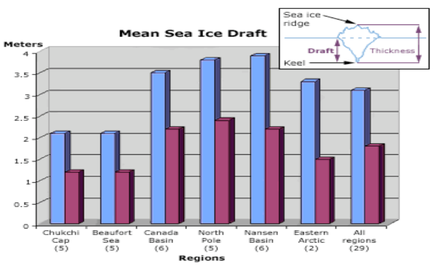
Parameter	Value
Precision	20 cm
Accuracy	10% of thickness
Thickness range	0.3 – 8 m and greater, Arctic and Antarctic
Horizontal sampling	500 m or less, 10-15 day orbital repeat
Product Description	Monthly average, gridded, mean and rms, distribution

Importance of Sea Ice Thickness and Snow Measurements

=> Most sensitive indicator of climate change in polar regions.

- Thickness is integrated effect of changes in atmospheric and oceanic circulation.
- Thickness distribution controlled by thermodynamic growth and decay, ice motion/advection, and mechanical redistribution.
- Snow cover on sea ice influences thermodynamic growth.

Arctic sea ice thickness has thinned by 40% over recent decades (3.1 to 1.8 m), as measured by submarine upward-looking sonar (Rothrock et al., 1999)

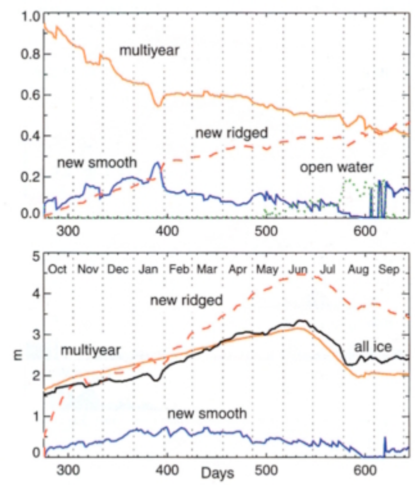


Measurement Use

=>First direct measurement of sea ice thickness from space.

- Determine sea ice growth rates.
- Determine thickness redistribution
- Determine sea ice mass balance, particularly in perennial ice.
- Validation and improvement of representation of thickness distribution in sea ice thermodynamic/dynamic models

Arctic thickness distribution



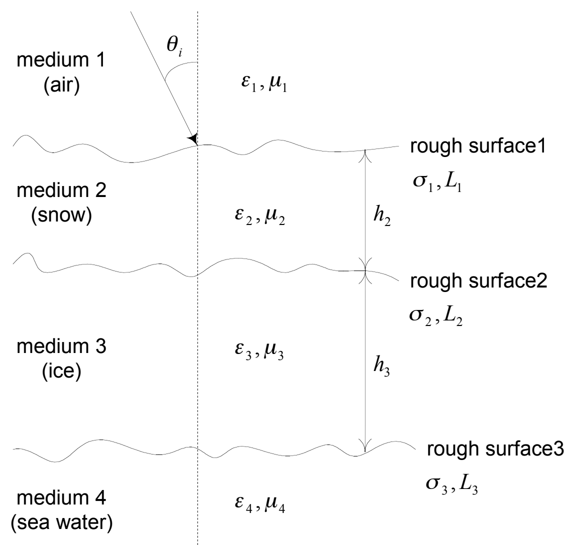
Right Panel. Area fraction (top) and mean thickness (bottom) of multiyear ice, new smooth ice, new ridged ice, and open water. In moving 200 by 200 km area. (Lindsay, 2003)

Problem Definition

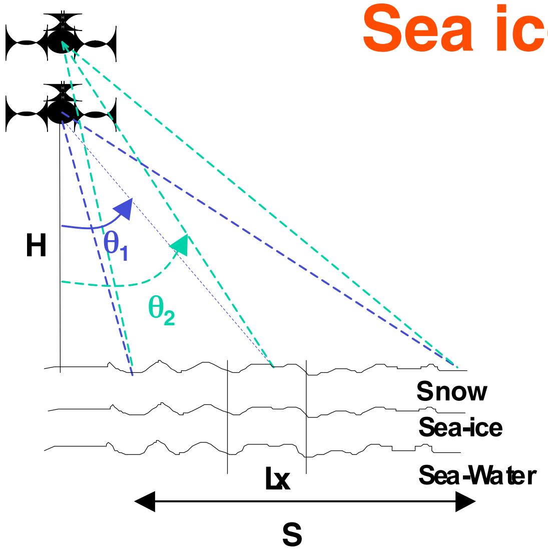
• Sea ice is a highly inhomogeneous medium consisting of lossy background ice with trapped air bubbles and brine inclusions. The surface is covered by snow and its compositions vary substantially over time and location.

• The scattered field is a complex expression of the snow cover, the surface roughness at the air-snow, snow-ice, and ice-water interfaces, the ice salinity, and the characteristics of the in- homogeneities (air bubbles, brine inclusion sizes) in the volume.

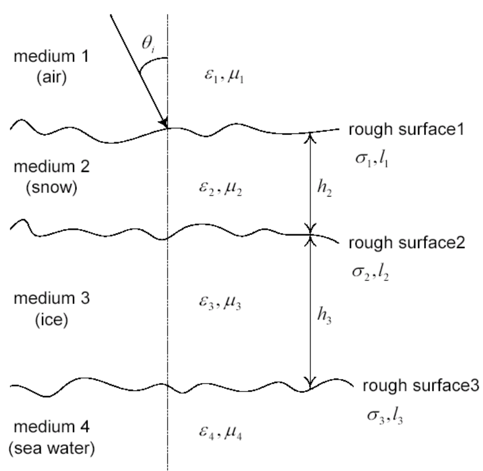
• Allocated RF bandwidth at VHF is limited to 1.0 MHz over US, and 1-6 MHz over International water.



Sea ice sensing model approach for VHF



- Sea ice is modeled as a four-layered medium.
- Each surface interface is modeled as a rough surface with a Gaussian roughness spectrum.
- Typical estimated parameters of the electrical properties of each layer of the medium and rough surface characteristics are based on published reports (Ulaby and Fung).



	Index of refraction	Layer thickness	Rms Height (cm)	Correlation length (cm)
Layer 1 snow	$\varepsilon_2 = 3.15 - j0.001$	$h_2 = 8cm$	$\sigma_1 = 0.024$	$l_1 = 0.12$
Layer 2 ice	$\varepsilon_3 = 4.0395 - j0.4329$	$h_3 = 2$ m	$\sigma_2 = 0.28$	$l_2 = 1.8$
Layer 3 sea water	$\varepsilon_4 = 57.9 - j39.8$		$\sigma_3 = 0.9$	$l_3 = 24$

	Radius	**Fractional volume**	**Dielectric constant**
Air bubbles	**0.5044 mm**	**4.3%**	**1**
Brine inclusions	**0.1276 mm**	**1.39%**	**60-j40**

Sea-ice sensing model approach for VHF

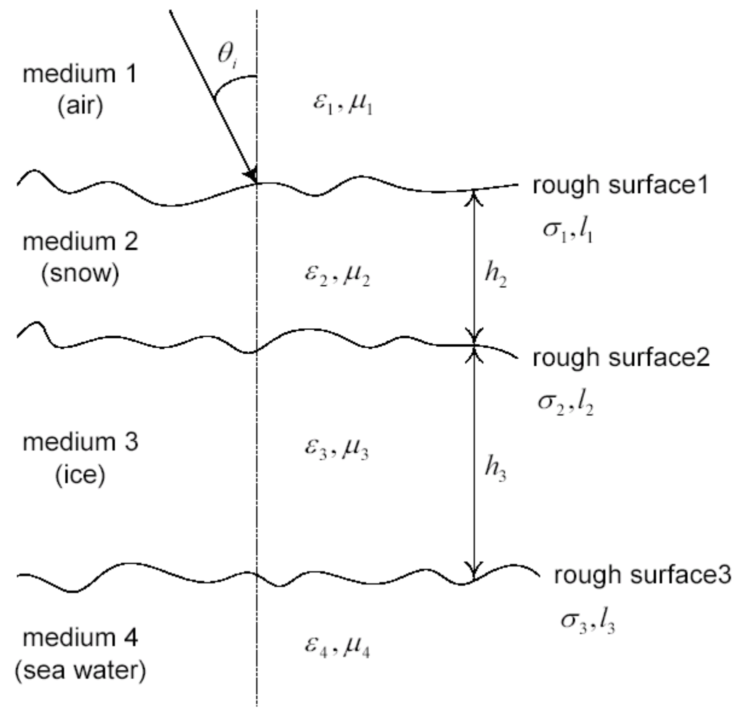
2 D Scattering model:

- EM waves propagating in the medium is separated into coherent and incoherent Waves:

a. Coherent waves propagation is based on the Transmission line model

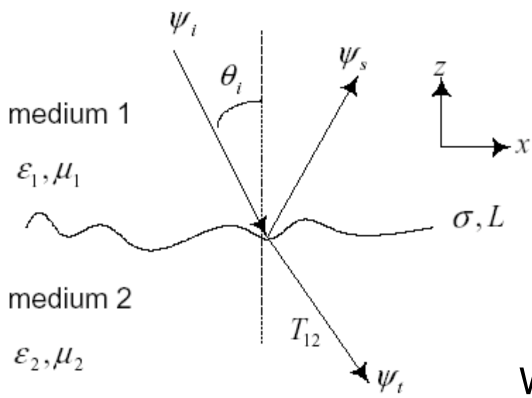
b. Incoherent waves are from

1) Rough surface scattering
   - Coherent part incidence on the rough surfaces
   - Small perturbation (for small roughness)
   - Kirchhoff approximation (for larger roughness, small slope)
2) Volume scattering
   - Rayleigh scattering from brine inclusions and air bubbles



Incoherent component : Small Perturbation Method

- SPM-2D – first order:



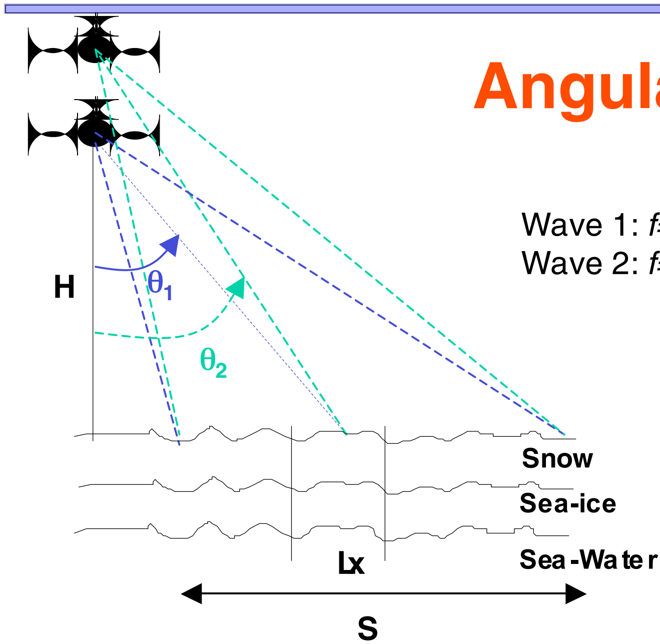
$$\begin{aligned}\psi_s^{(1)}(\bar{r}) &= -\int d\bar{k}_\perp e^{-j\bar{k}_\perp \bar{r}_\perp - jk_z z} jH(\bar{k}_\perp - \bar{k}_{i\perp}) \\ &\quad \left\{ \begin{array}{l} \hat{e}(k_z)\left[f_{ee}^{(1)}(\bar{k}_\perp, \bar{k}_{i\perp})\left(\hat{e}(-k_{iz})\cdot\hat{e}_i\right) + f_{eh}^{(1)}(\bar{k}_\perp, \bar{k}_{i\perp})\left(\hat{h}(-k_{iz})\cdot\hat{e}_i\right)\right] \\ +\hat{h}(k_z)\left[f_{he}^{(1)}(\bar{k}_\perp, \bar{k}_{i\perp})\left(\hat{e}(-k_{iz})\cdot\hat{e}_i\right) + f_{hh}^{(1)}(\bar{k}_\perp, \bar{k}_{i\perp})\left(\hat{h}(-k_{iz})\cdot\hat{e}_i\right)\right] \end{array} \right\} \\ &\triangleq -\int d\bar{k}_\perp e^{-j\bar{k}_\perp \bar{r}_\perp - jk_z z} jH(\bar{k}_\perp - \bar{k}_{i\perp}) S(\bar{k}_\perp, \bar{k}_{i\perp}) \\ &= -j2k_z H(\bar{k}_\perp - \bar{k}_{i\perp}) S(\bar{k}_\perp, \bar{k}_{i\perp}) \left(\frac{e^{-jkR}}{4\pi R} \right) \quad \text{For far field}\end{aligned}$$

Where

$$H(k_\perp - k_{i\perp}) = \iint h(x,y)\exp\left(-j(k_x - k_{xi})x\right)dx\exp\left(-j(k_y - k_{yi})y\right)dy$$

is the Fourier transform of the random height function h(x,y)

Angular-And Frequency Correlation



Wave 1: f=137 MHz, θ_1=30°, =-30°
Wave 2: f=162 MHz, θ_2=25°, =-25°

•The correlation between two waves with different frequencies, incidence and observation angles, is employed, forming a combined spatial- and frequency-domain interferometer.

$$\Gamma(\theta_{i1},\theta_{s1},f_1;\theta_{i2},\theta_{s2},f_2) =< E_{s1}(\theta_{i1},\theta_{s1},f_1); E^*_{s2}(\theta_{i2},\theta_{s2},f_2) >$$

•This technique exploits the difference in the correlation properties (phase matching conditions) of surface and volume scattering. The surface correlation function exhibits a strong correlation along a “memory line.” The volume scattering shows a strong correlation at specific points – “memory dots.”

Angular-And Frequency Correlation

- Total scattered waves are combination of rough surface scattering from all the surfaces, (air-snow, snow sea-ice, sea-ice sea water), and volume scattering from inclusions in layers (air bubles and brines).

- For modeling purposes, we assume volume and surface scattering are independent

- The correlation of scattered waves is the summation of the correlation of wave from each rough surface and correlation of wave from volume scattering

$$\gamma = \langle \psi_t \psi_t^* \rangle = \langle \psi_{s1} \psi_{s1}^* \rangle + \langle \psi_{s2} \psi_{s2}^* \rangle + \langle \psi_{s3} \psi_{s3}^* \rangle + \langle \psi_{v1} \psi_{v1}^* \rangle + \langle \psi_{v2} \psi_{v2}^* \rangle = \Gamma e^{i\phi}$$

Coherence

Phase

- To maximize the desired surface scattering and to minimize the volume scattering effects, we can choose appropriate combinations of incident and observation angles for both waves

Correlation function based on SPM

- Surface 1

$$\left\langle \psi_{s1}(k)\psi_{s1}^{*}(k')\right\rangle = 4k_z k_z' \left\langle H_1(\bar{k}_\perp - \bar{k}_{i\perp}) H_1^{*}(\bar{k}_\perp' - \bar{k}_{i\perp}')\right\rangle$$

$$S_1(\bar{k}_\perp, \bar{k}_{i\perp}) S_1^{*}(\bar{k}_\perp', \bar{k}_{i\perp}') \left(\frac{e^{-j(k-k')R}}{(4\pi R)^2} \right) \psi_{id1}(k)\psi_{id1}(k')$$

- Surface 2

$$\left\langle \psi_{s2}(k)\psi_{s2}^{*}(k')\right\rangle = 4k_z k_z' \left\langle H_2(\bar{k}_\perp - \bar{k}_{i\perp}) H_2^{*}(\bar{k}_\perp' - \bar{k}_{i\perp}')\right\rangle T_{21} T_{21}'^{*} S_2(\bar{k}_\perp, \bar{k}_{i\perp}) S_2^{*}(\bar{k}_\perp', \bar{k}_{i\perp}')$$

$$\left(\frac{e^{-j(k-k')R}}{(4\pi R)^2} \right) \exp(-j(q_2 - q_2')h_2) \psi_{id2}(k)\psi_{id2}(k')$$

- Surface 3

$$\left\langle \psi_{s3}(k)\psi_{s3}^{*}(k')\right\rangle = 4k_z k_z' \left\langle H_3(\bar{k}_\perp - \bar{k}_{i\perp}) H_3^{*}(\bar{k}_\perp' - \bar{k}_{i\perp}')\right\rangle$$

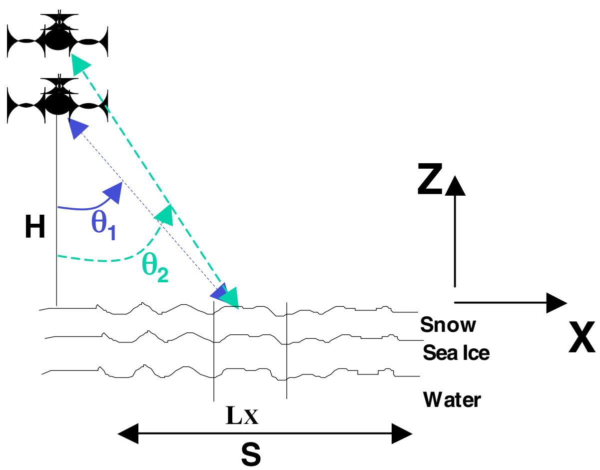
$$S_3(\bar{k}_\perp, \bar{k}_{i\perp}) S_3^{*}(\bar{k}_\perp', \bar{k}_{i\perp}') \left(\frac{e^{-j(k-k')R}}{(4\pi R)^2} \right) T_{21} T_{21}'^{*} T_{32} T_{32}'^{*}$$

$$\exp(-j(q_2 - q_2')h_2) \exp(-j(q_3 - q_3')h_3) \psi_{id3}(k)\psi_{id3}(k')$$

Height correlation evaluation

$$\left\langle H_i(\bar{k}_\perp - \bar{k}_{i\perp}) H_i^*(\bar{k}'_\perp - \bar{k}'_{i\perp}) \right\rangle$$

$$\left\langle H_i(\bar{k}_\perp - \bar{k}_{i\perp}) H_i^*(\bar{k}'_\perp - \bar{k}'_{i\perp}) \right\rangle = \pi^2 \sigma_i^2 l_i^2 L_{xeq} L_{yeq} \exp\left(-\frac{A_{cx}^2 l^2}{4}\right) \exp\left(-\frac{A_{dx}^2 L_{xeq}^2}{4}\right) \exp\left(-\frac{A_{cy}^2 l^2}{4}\right) \exp\left(-\frac{A_{dy}^2 L_{yeq}^2}{4}\right)$$



$$A_c = A_{cx} + A_{cy}$$

$$A_{cx} = \frac{1}{2}\left[k\left(\sin\theta\cos\phi - \sin\theta_i\cos\phi_i\right) + k'\left(\sin\theta'\cos\phi' - \sin\theta'_i\cos\phi'_i\right)\right]$$

$$A_{cy} = \frac{1}{2}\left[k\left(\sin\theta\sin\phi - \sin\theta_i\sin\phi_i\right) + k'\left(\sin\theta'\sin\phi' - \sin\theta'_i\sin\phi'_i\right)\right]$$

$$A_d = A_{dx} + A_{dy}$$

$$A_{dx} = \left[k\left(\sin\theta\cos\phi - \sin\theta_i\cos\phi_i\right) - k'\left(\sin\theta'\cos\phi' - \sin\theta'_i\cos\phi'_i\right)\right]$$

$$A_{dy} = \left[k\left(\sin\theta\sin\phi - \sin\theta_i\sin\phi_i\right) - k'\left(\sin\theta'\sin\phi' - \sin\theta'_i\sin\phi'_i\right)\right]$$

$$\frac{1}{L_{xeq}^2} = \frac{1}{2}\left(\frac{1}{L_x^2} + \frac{1}{(L'_x)^2}\right); \quad \frac{1}{L_{yeq}^2} = \frac{1}{2}\left(\frac{1}{L_y^2} + \frac{1}{(L'_y)^2}\right)$$

Simple system: Observation in the backscatter direction

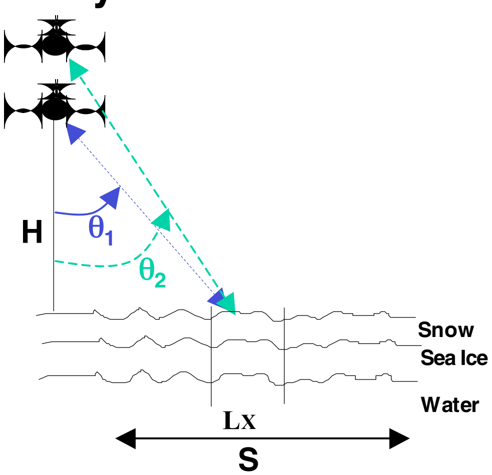
- Since $\beta(\sin\theta_{s1} - \sin\theta_{i1}) = \beta'(\sin\theta'_{s2} - \sin\theta'_{i2})$, let $\theta_{s1} = -\theta_{i1}$ and $\theta'_{s2} = -\theta'_{i2}$ (backscattering), then $\boldsymbol{\beta \sin\theta_{i1} = \beta' \sin\theta'_{i2}}$

Coherence

$$\gamma = \langle \psi_t \psi_t^* \rangle = \langle \psi_{s1}\psi_{s1}^* \rangle + \langle \psi_{s2}\psi_{s2}^* \rangle + \langle \psi_{s3}\psi_{s3}^* \rangle + \langle \psi_{v1}\psi_{v1}^* \rangle + \langle \psi_{v2}\psi_{v2}^* \rangle = \Gamma e^{i\phi}$$

Phase

- **Estimation of sea-ice thickness is provided by combining data, γ, from <u>two radar beams</u>. That is, two waves with different frequencies, incident angles and observation angles in the backscatter direction are correlated. (Angular and frequency correlation, γ, between two radar beams/or combined spatial and frequency domain interferometer).**

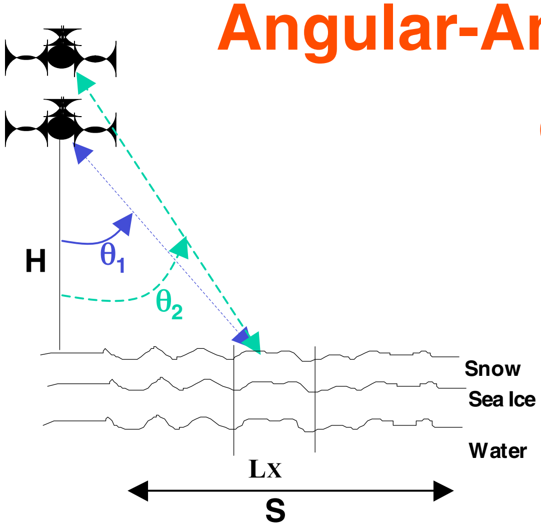


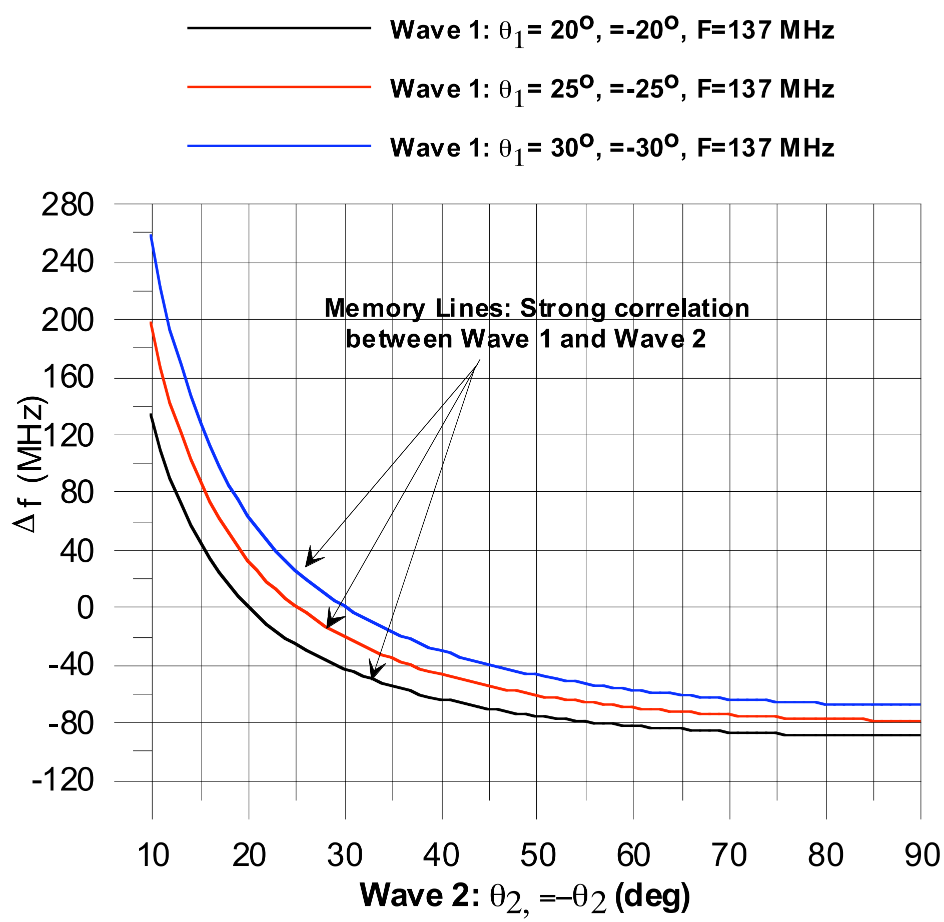
VHF- Radar System

	Beam 1	Beam 2
Frequency	137 MHz	162 MHz
Incidence	θ_1= 30 deg	$\theta_{2=}$ 25 deg

Angular-And Frequency Correlation:Simple System

Observation in the backscatter direction





- **On Memory: Line strong correlation between**

  Wave 1 : f=137 MHz, θ_1=30 degree, =-30 degree

  Wave 2 : f=162 MHz, θ_2=25 degree, =-25 degree

  → Δf = 25.08 MHz

- **On Memory Line: strong Correlation between**

  Wave 1 : f=137 MHz, θ_1=30 degree, =-30 degree

  Wave 2 : f=150.88 MHz, θ_2=27 degree, =-27 degree

  → Δf = 13.88 MHz

Correlation function from volume scattering

$$\left\langle \psi_{v1}(k)\psi_{v2}^{*}(k')\right\rangle = \frac{\exp(-jkR_1 + jk'R_2)}{R_1R_2} f(k) f^{*}(k')\psi_d(k)\psi_d^{*}(k')\exp\left(-\left\{\gamma_2+\gamma_2'^{*}\right\}\cdot h_2\right)$$
$$T_{32}(k)T_{32}^{*}(k')T_{21}(k)T_{21}^{*}(k')\rho\int_{V_c} dv_c \exp\left(A_{dx}x_c + A_{dy}y_c + A_{dz}z_c\right)$$

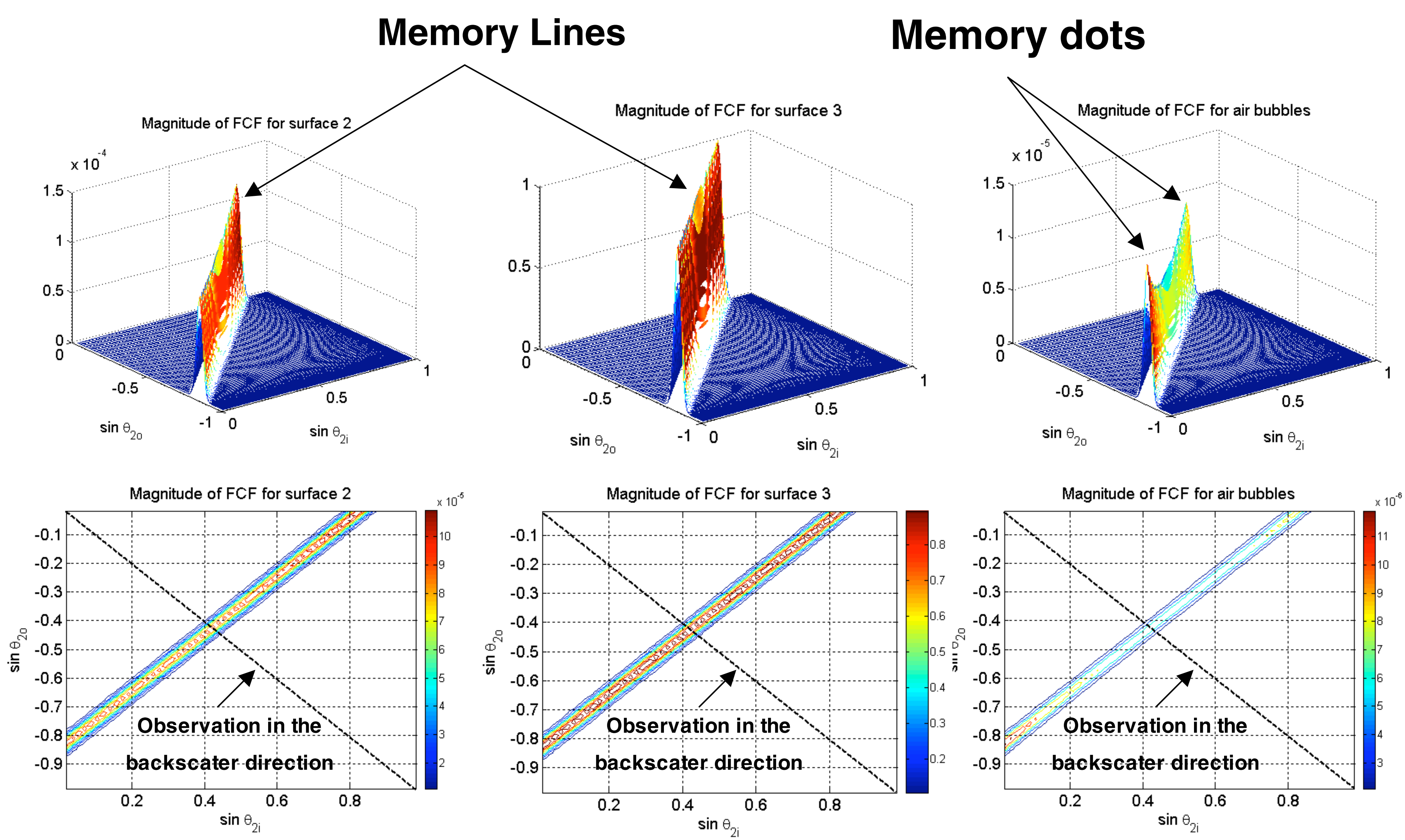
$$\int_{V_c} dv_c \exp\left(A_{dx}x_c + A_{dy}y_c + A_{dz}z_c\right) = \pi L_{xeq}L_{yeq}\exp\left(-\frac{A_{dx}^2L_{xeq}^2}{4} - \frac{A_{dy}^2L_{yeq}^2}{4}\right)\frac{\left[1-\exp(-A_{dz}d)\right]}{A_{dz}}$$

$$A_{dx} = \beta(\sin\theta\cos\phi - \sin\theta_i\cos\phi) - \beta'(\sin\theta\cos\phi - \sin\theta_i\cos\phi)$$
$$A_{dy} = \beta(\sin\theta\sin\phi - \sin\theta_i\sin\phi) - \beta'(\sin\theta\sin\phi - \sin\theta_i\sin\phi)$$
$$A_{dz} = j\beta(\cos\theta + \cos\theta_i) + 2\alpha - j\beta'(\cos\theta + \cos\theta_i) + 2\alpha'$$

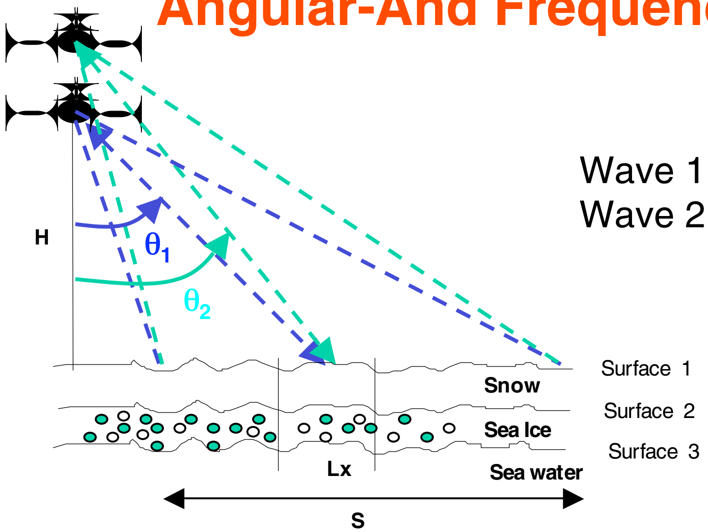
T_{32} is the transmission coefficient from ice to snow

T_{21} is the transmission coefficient from snow to air

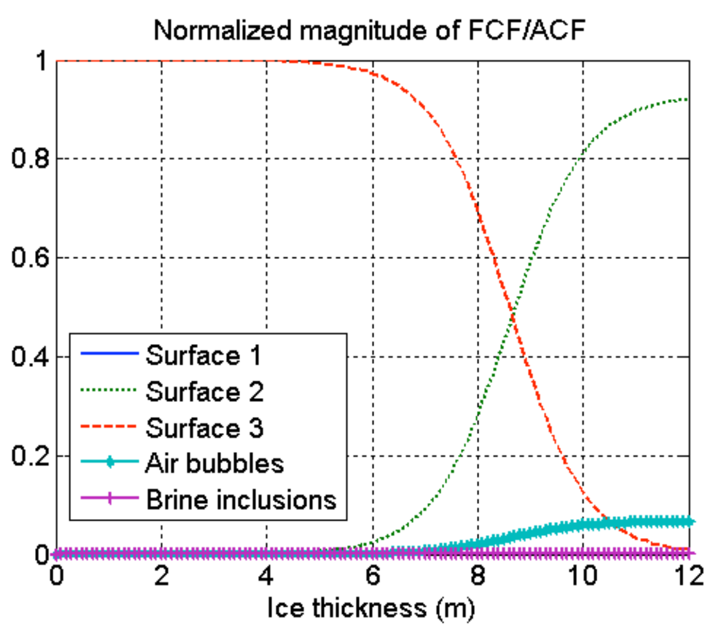
SPM– memory lines, memory dots: 3D Geometry

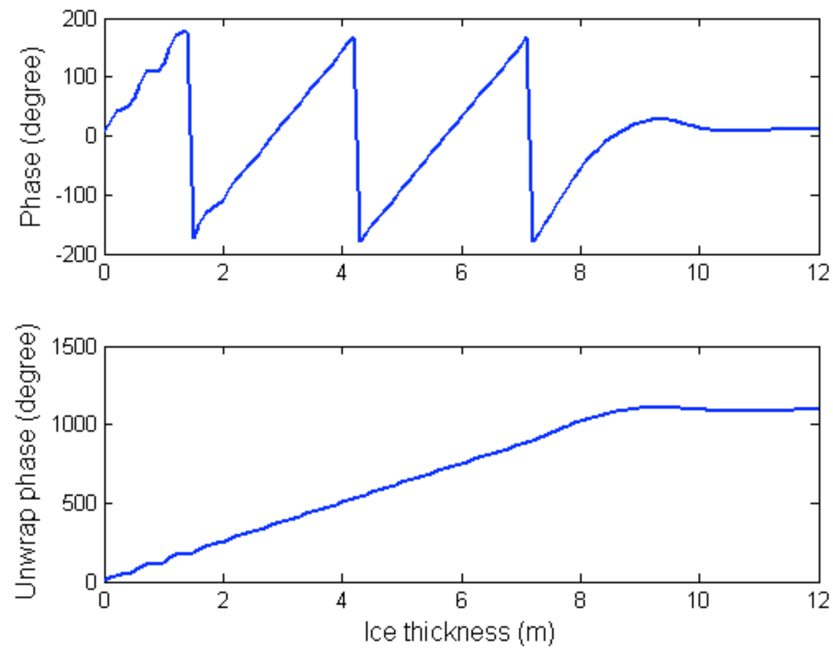


Angular-And Frequency Correlation (AFC/FCF) vs ice thickness



Wave 1: f=137 MHz, θ_1=30°, =-30°
Wave 2: f=162 MHz, θ_2=25°, =-25°

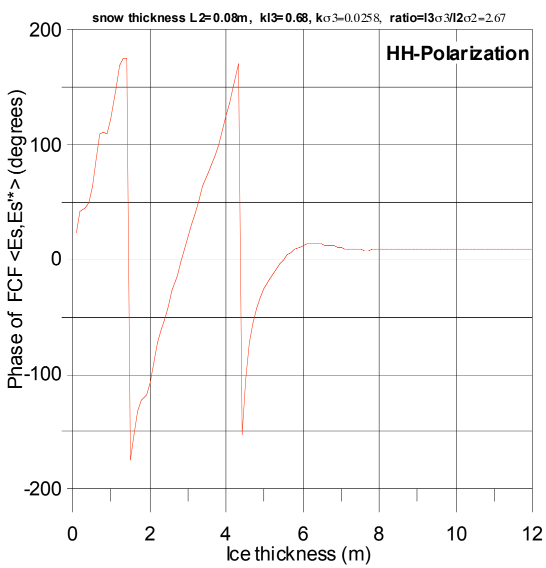




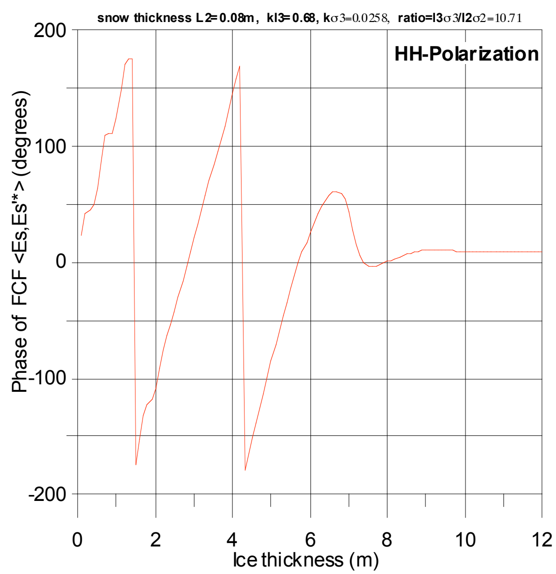
Angular-And Frequency Correlation (AFC/FCF): 3D Geometry

- **The phase of the ACF/FCF and consequently thickness estimation depth is impacted by the ratio of surface roughness characteristics of sea-ice sea water interface, σ_3 L_3, to snow sea ice interface σ_2 L_2 → Large ratio indicates bottom surface interface amplitude dominates and phase linearity extends deeper than smaller ratio.**

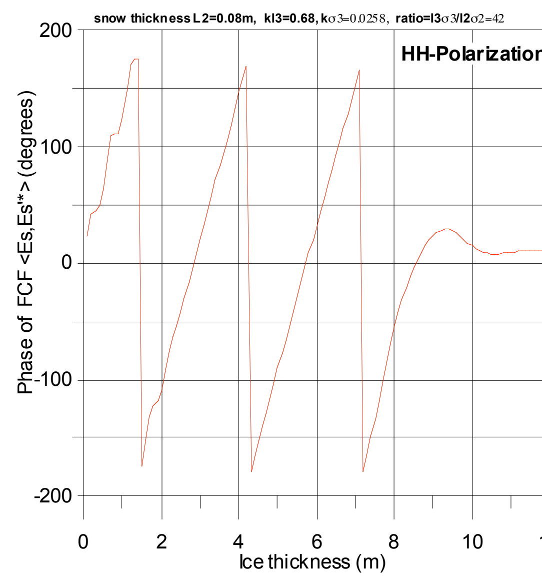
$$\frac{\sigma_3 L_3}{\sigma_2 L_2} = 2.67$$



$$\frac{\sigma_3 L_3}{\sigma_2 L_2} = 10.71$$

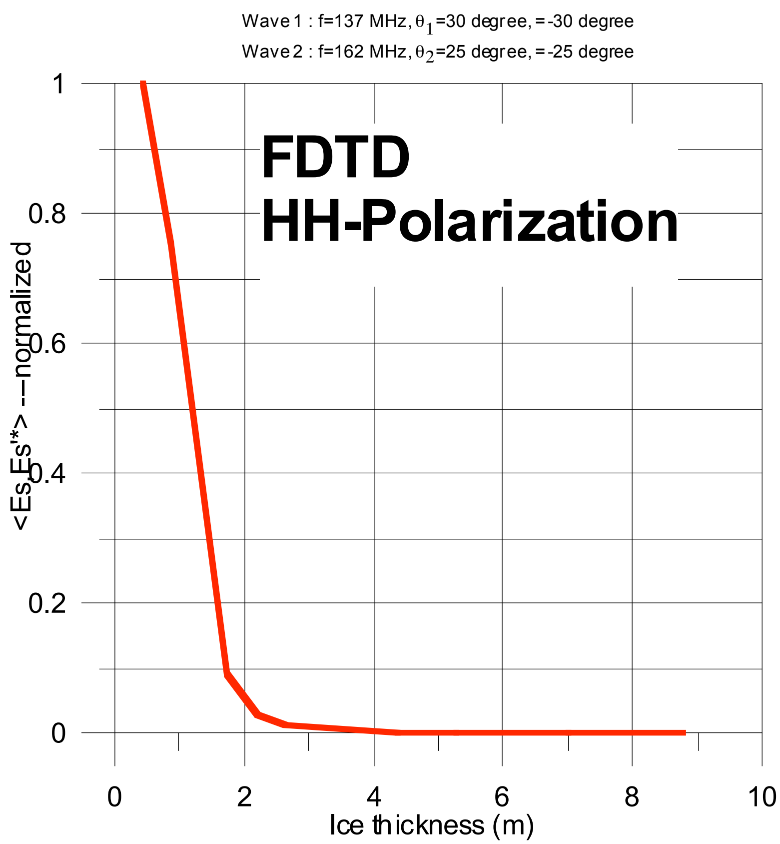


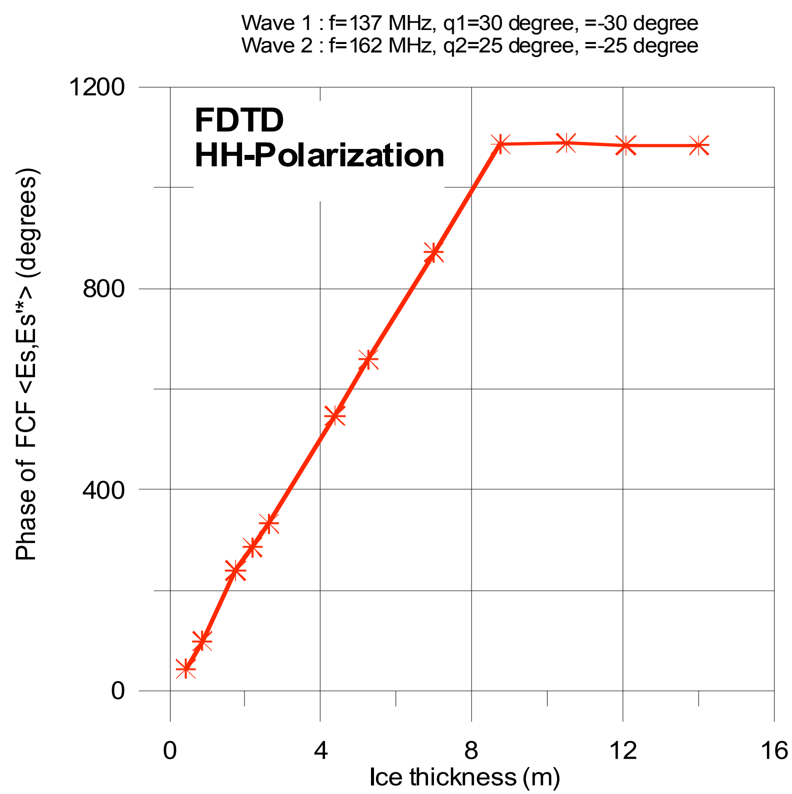
$$\frac{\sigma_3 L_3}{\sigma_2 L_2} = 42$$



Angular-And Frequency Correlation (AFC/FCF)

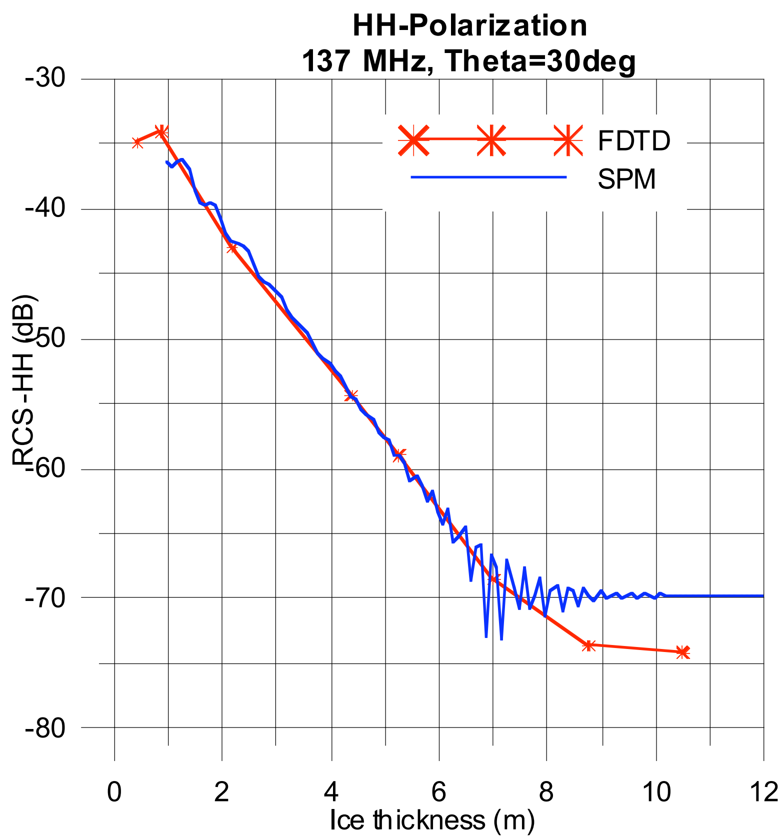
- We validate the ACF/FCF analytical model based on small pertubation method (SPM) for 3D geometry with Finite difference Method (FDTD)
- We observe ACF/FCF phase linearity for both methods extend up to ~ 8 m as shown below and previous slide for $\sigma 3$ L3/ $\sigma 2$ L2 =42

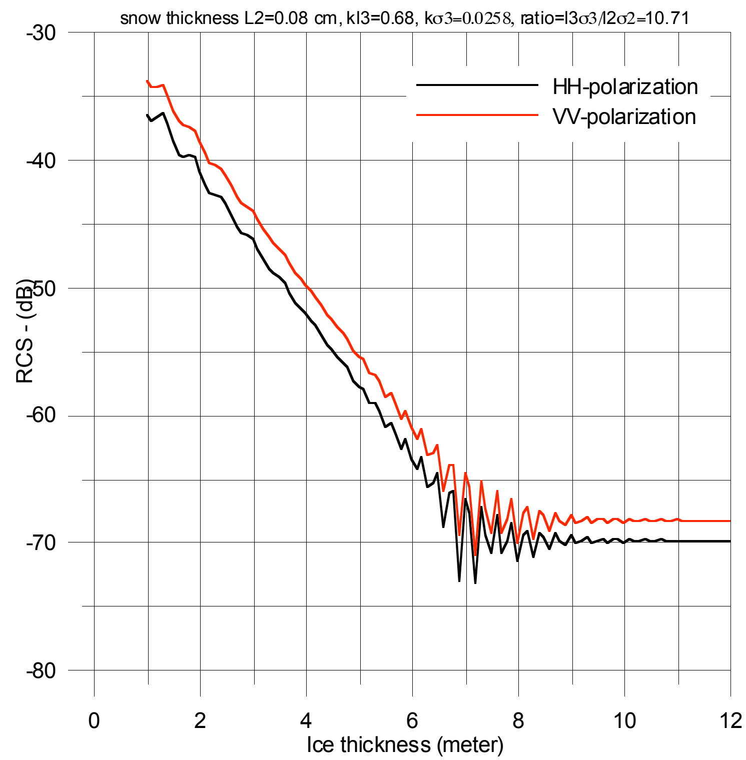




Backscattered Signal Based on FDTD and SPM

- We validate the RCS analytical model based on small pertubation method (SPM) with Finite difference Time Domain (FDTD) method





Sea-Ice Thickness Estimation

• Estimation of the height, of the sea-ice is based <u>on the phase information</u> of the angular and frequency Correlation (AFC/FCF) Functions. To calculate the phase of the AFC/FCF, $\Psi(h)$, two waves with different frequencies, incident angles and observation angles are correlated.

Inversion Technique:

- **Gradient Descent (GD)**
- **Least Square method (LSQ)**
- **Genetic Algorithm (GA)**

Gradient descent method (GD)

The objective is to minimize the function $\left(\psi(h)-\psi_m\right)^2$
where $\psi(h)$ is the expression of phase of FCF as a function of ice thickness h, which we have in the forward model, and the ψ_m is the 'measured' phase of FCF, which can be calculated using the forward model.

Let h_0 be the first guess of ice thickness explained above, a better guess using the gradient descent search is obtained by

$$h_1 = h_0 - \mu \left.\frac{\partial \psi(h)}{\partial h}\right|_{h_0} \left(\psi(h)-\psi_m\right)$$

where μ is the step size. The derivative $\left.\frac{\partial \psi}{\partial h}\right|_{h_0}$ can be found numerically by

$$\left.\frac{\partial \psi}{\partial h}\right|_{h_0} = \frac{\psi(h_0+\varepsilon)-\psi(h_0)}{\varepsilon}$$

This process is iterated until $\left|h_{new}-h_{old}\right| < \rho$ where ρ is a preset threshold. Then, h_{new} is the answer.

Sea-Ice Thickness Estimation

- **Genetic Algorithm (GA): A global optimization and search method, seeking extrema of an objective function/fitness function - That is a measure of system performance-, you start with a set of initial values (Generate initial population) of sea ice thickness, *h*.**

- **GA doesn't operate directly on the parameters, h, but rather on the objective function. GA simultaneously optimize entire populations, h, rather than single population at a time. No derivative is required.**

- **We employ a fitness function of the form**

$$fitness = e^{-(\psi_m - \psi(h))^2}$$

where $\psi(h)$ is the phase of ACF/FCF calculated from forward model, and ψ_m is the measured phase of ACF/FCF– in this case the phase is obtained from simulated forward data.

- **Gradient Descent (GD) and Least Square (LSQ) Methods: Local optimization approach, you start with a single guess value of sea ice thickness, requires the knowledge of the derivative of the ACF/FCF**

Angular and Frequency Correlation: Sea-ice Thickness Retrieval By Genetic Algorithm (GA)

Case 1: True Sea-Ice Thickness is 0.5 m

First Generation:

h Ice Thickness (m)	ψ_m True Phase (radian)	$\psi(h)$ Estimated Phase (radian)	$fitness = e^{-(\psi_m - \psi(h))^2}$ F(h)
0.561846	3.240871	3.107539	0.98238
0.141026	3.240871	3.638501	0.85376
0.098178	3.240871	3.749308	0.77220
0.653218	3.240871	2.839860	0.85145
0.791803	3.240871	2.536849	0.60918

First Random Guess

Population size 5

Bad gene

Fitness Function/How good?

Angular and Frequency Correlation: Sea-ice Thickness Retrieval By Genetic Algorithm (GA)

Case 1: True Sea-Ice Thickness is 0.5 m

Second Generation:

Element with higher probability to cross over

h Ice Thickness (m)	$\psi_m(h)$ True Phase (radian)	$\psi(h)$ Estimated Phase (radian)	$fitness = e^{-(\psi_m(h)-\psi(h))^2}$ F(h)
0.559832	3.240871	3.112555	0.98367
0.016999	3.240871	3.909515	0.63949
0.098178	3.240871	3.749308	0.77220
0.561846	3.240871	3.107539	0.98238
0.641530	3.240871	2.876902	0.87593

Survive from 1st generation

Selection/Cross Over /mutation

Angular and Frequency Correlation: Sea-ice Thickness Retrieval By Genetic Algorithm (GA): 2D Geometry

Case 1: True Sea-Ice Thickness is 0.5 m

60th Generation:

Ice Thickness (m)	True Phase (radian)	Estimated Phase (radian)	F(h)
0.500290	3.240871	3.240343	~1
0.500259	3.240871	3.240398	~1
0.500290	3.240871	3.240343	~1
0.501267	3.240871	3.238555	0.99603
0.500259	3.240871	3.240398	~1

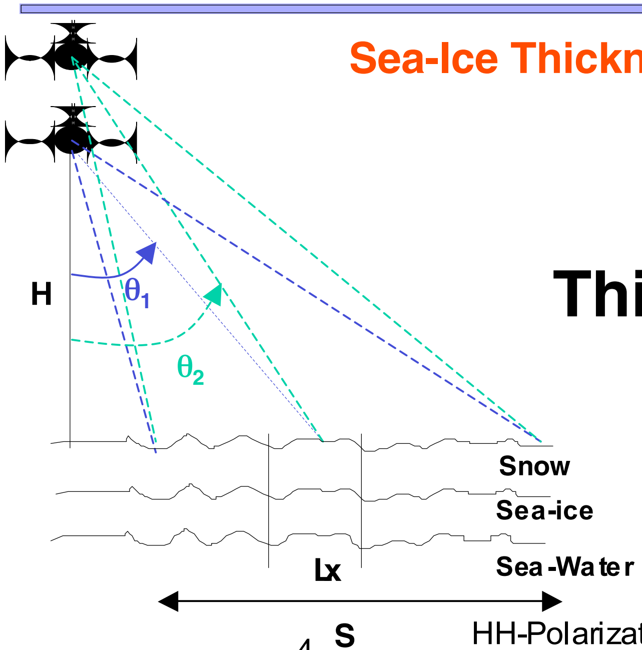
Sea-Ice Thickness Estimation By Genetic Algorithm:3D Geometry

- **Thickness estimation from 0.4 m to 3.6 m**

VV-Polarization

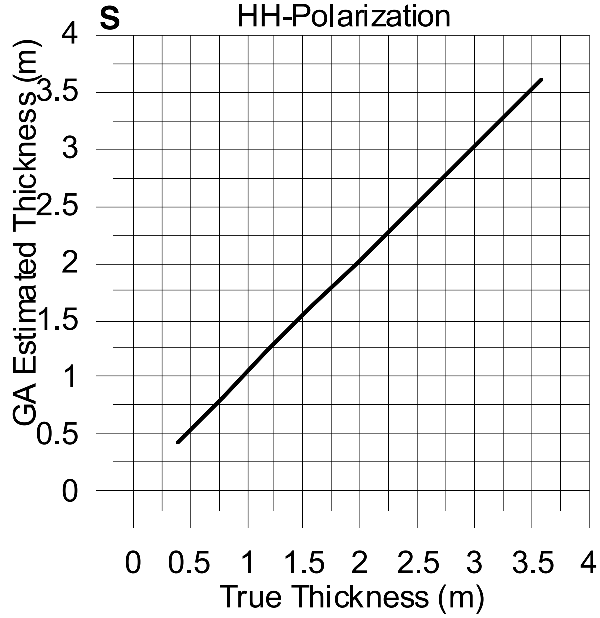
Genration #	True Thickness (m)	GA Estimated Thickness (m)	True Phase (rad)	GA Average Phase (rad)	fitness
22	0.4	0.399157689	0.911501763	0.910240382	0.99999811
35	0.800000006	0.801196326	1.922591692	1.922666927	0.99999995
114	1.200000012	1.198828089	2.90734624	2.904653934	0.9999919
67	1.600000018	1.600781274	-2.656235032	-2.653438424	0.99998963
58	2.000000024	2.000402844	-1.873679106	-1.872670632	0.99999859
30	2.40000003	2.39971923	-0.943387254	-0.943892675	0.99999957
125	2.800000036	2.801257363	-0.062718241	-0.059999237	0.99999248
29	3.200000042	3.198608356	0.781783507	0.778886107	0.99999159
25	3.6	3.601806696	1.673959378	1.677228174	0.99998926

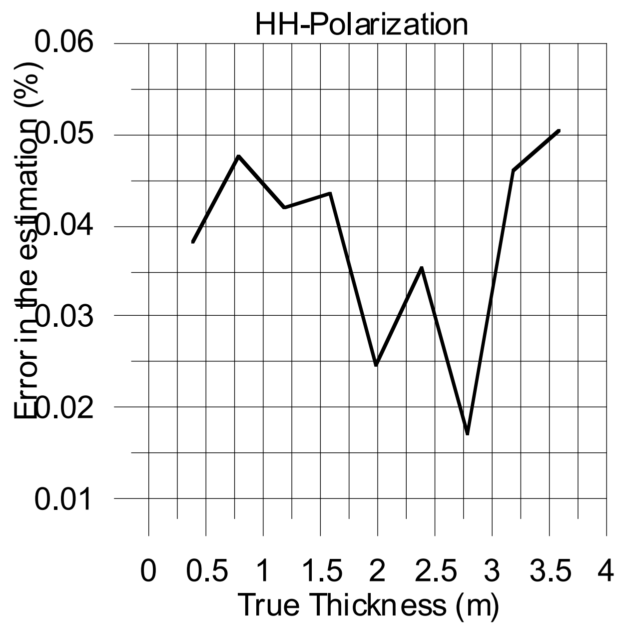
Sea-Ice Thickness Estimation By Genetic Algorithm:3D Geometry



HH-Polarization

Thickness estimation from 0.4 m to 3.6 m

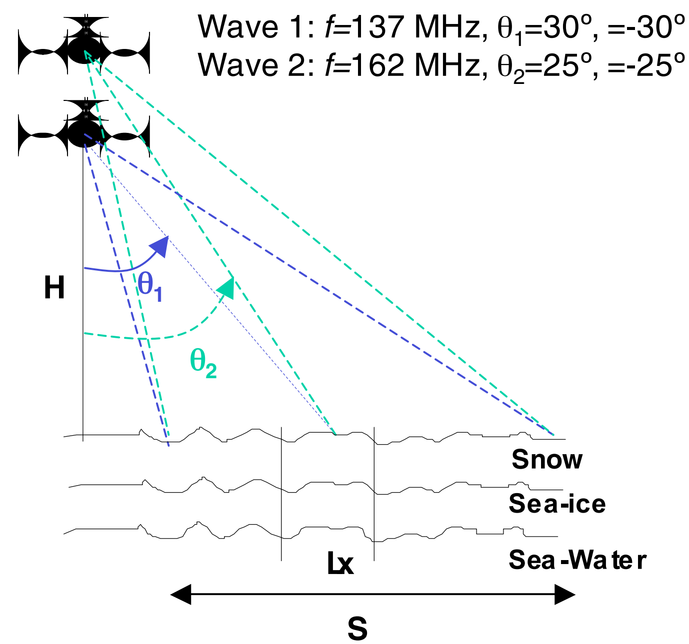




Prototype Instrument Technology: Summary Description

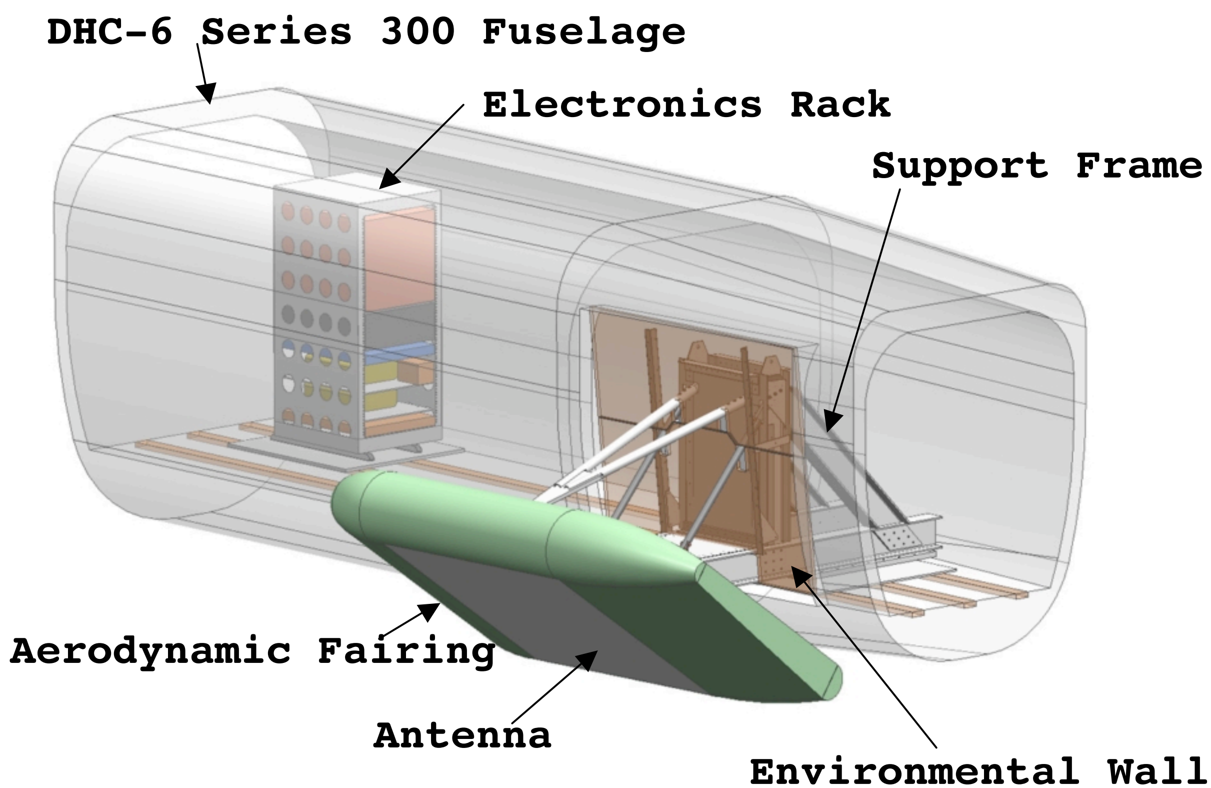
- The cryospheric advanced sensor (CAS) developed for technology demonstration and to investigate the sea ice thickness estimation techniques is a VHF side looking radar installed on a Twin Otter aircraft operating at a nominal 1 kilometer altitude.

- The CAS system is very flexible in its design and can operate at any frequency within the pass band of the antenna system. The radar can operate in a quad-polarization configuration and acquire data at any polarization. The following polarizations are possible:
  - Horizontal Transmit, Horizontal Receive
  - Horizontal Transmit, Vertical Receive
  - Vertical Transmit, Vertical Receive
  - Vertical Transmit, Horizontal Receive



Prototype Instrument Technology: Hardware Configuration

- A frame anchored to the cabin floor is cantilevered out the doorway to suspend the CAS antenna outside the fuselage.
- An environmental wall covers the doorway opening to preserve cabin temperature and protect occupants.
- An aerodynamic fairing surrounds the antenna to reduce drag.
- All radar and power electronics are located in a single rack fastened to the aircraft floor inside the cabin



Prototype Instrument Technology: radar design parameters

- In its nominal configuration, CAS operates at two frequencies in a side looking configuration. The operating frequencies to verify the Angular and Frequency correlation approach are nominally 137 MHz and 162 MHz center frequencies.

- The radar system will operate using a CHIRP transmitted waveform at both frequencies, each with a nominal 20 MHz bandwidth and a 2.5 microsecond transmit pulse duration.

- After radar data is acquired, the returns will be separated into two separate frequency bands (137 MHz and/or 162 MHz), then compressed in the processor prior to data analysis.

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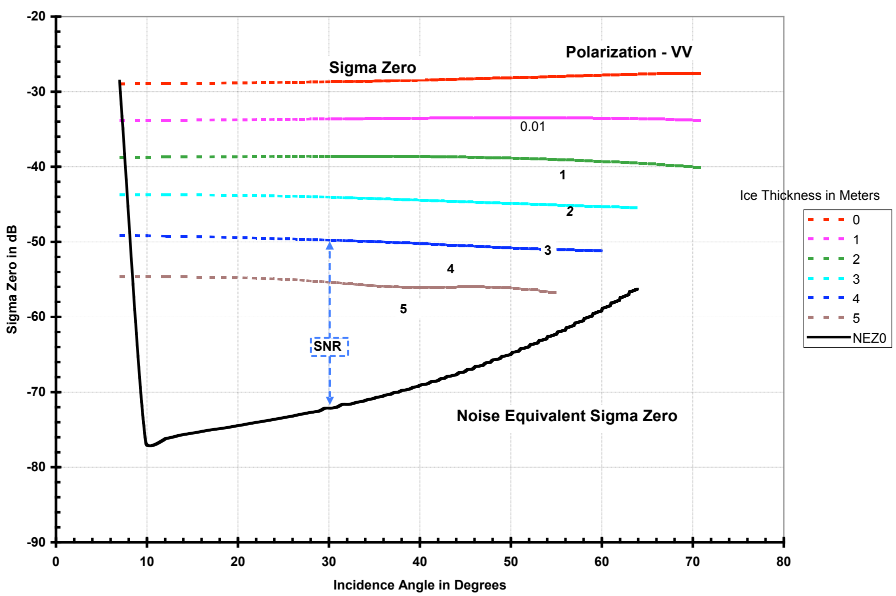
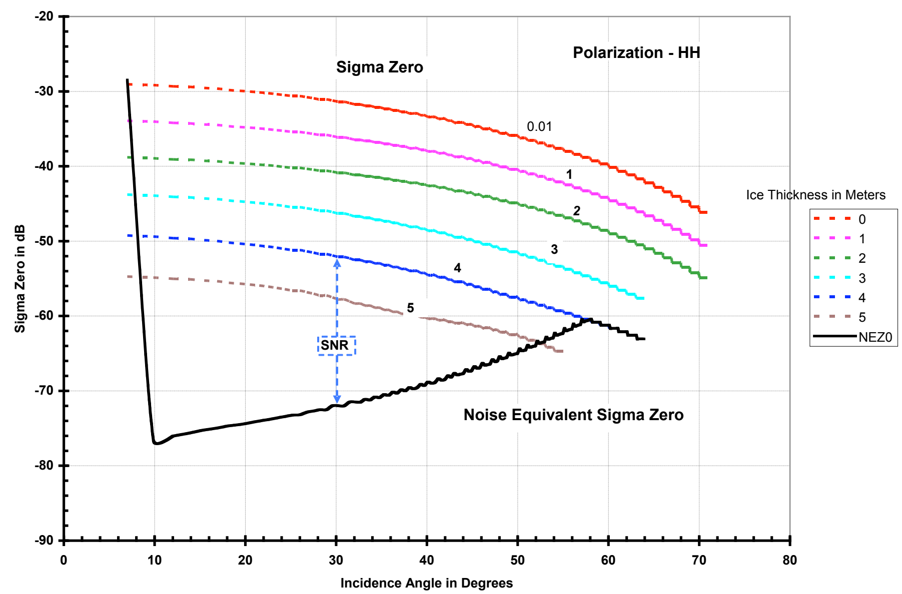
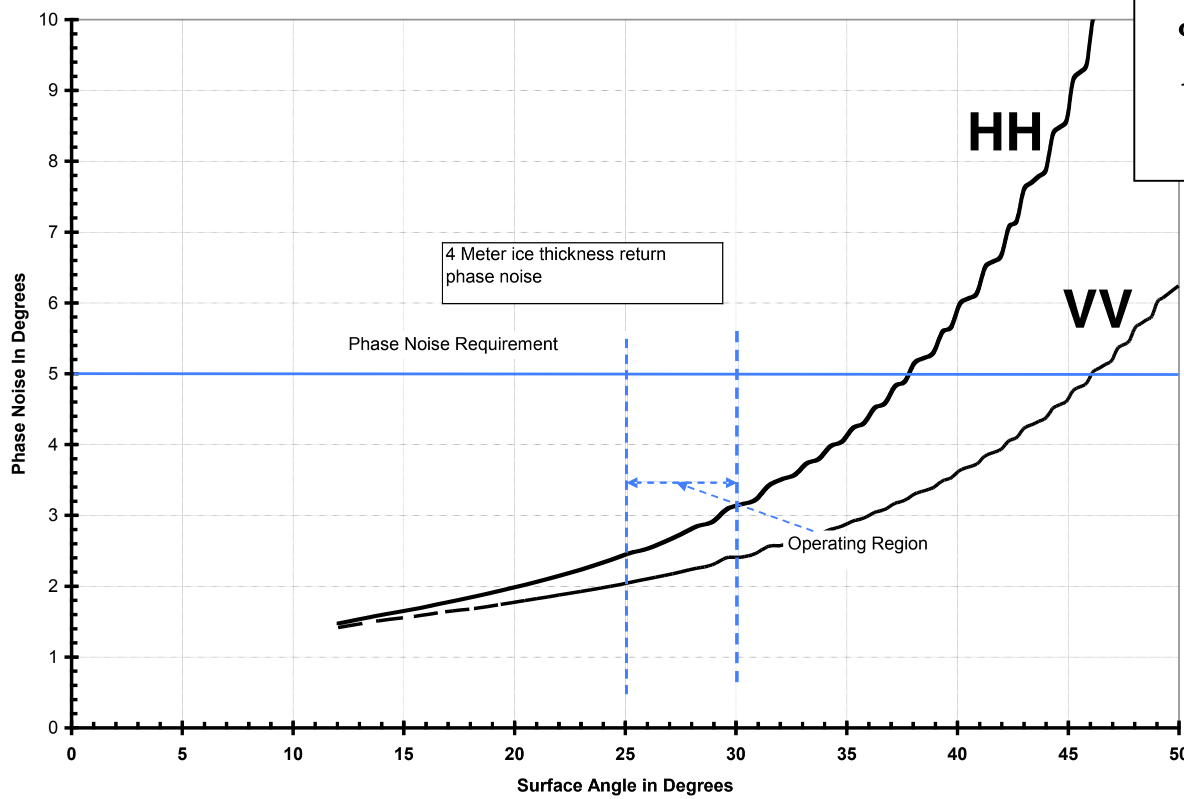
Sigma Zero and System Sensitivity

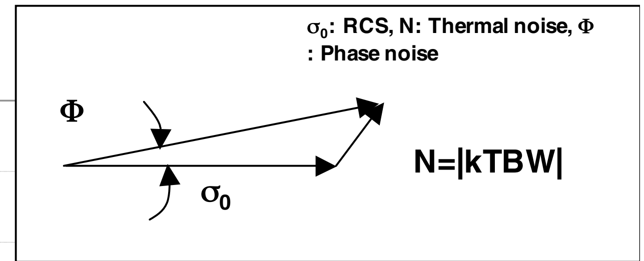




Phase Noise for Ice Thickness of 4 meters

- We assume that the noise is thermal noise.
- In our ACF/FCF calculations, we have sensitivity of 3 meters per 360 degree, which means an error of about 0.8 cm per degree.



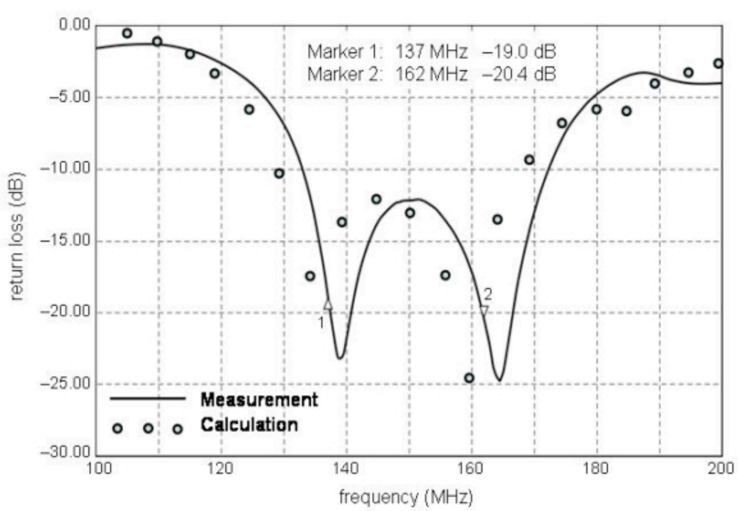


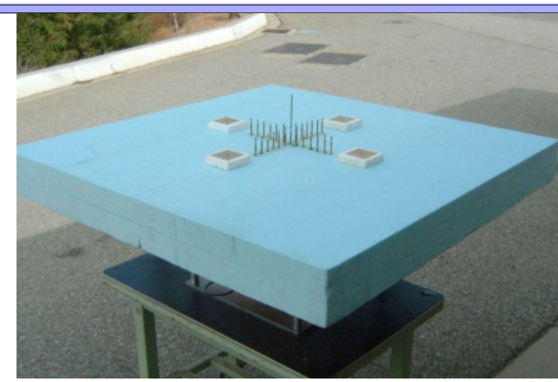
Technology Development: antenna design

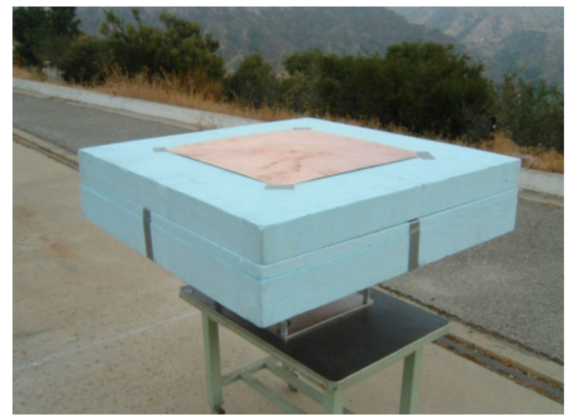
- A dual-polarized and broadband lightweight multi-layer VHF (127-172 MHz) microstrip antenna has been designed, developed, and tested.
- This antenna design allows us to acquire two separate measurements from different altitudes (1.0 km and 1.2 km), with each measurement being at separate frequencies.

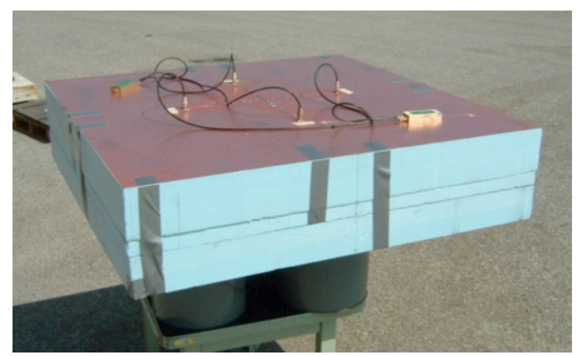
- A four capacitive feeding approach for the antenna with 180-degree hybrid connecting the two opposing probes and shorting pins are used to suppress the higher order modes presented in the thick multi-layer antenna substrate.

- This feeding approach to achieve better than 30 dB isolation between the antenna H- and polarization ports









CAS wideband dual-pol microstrip antenna

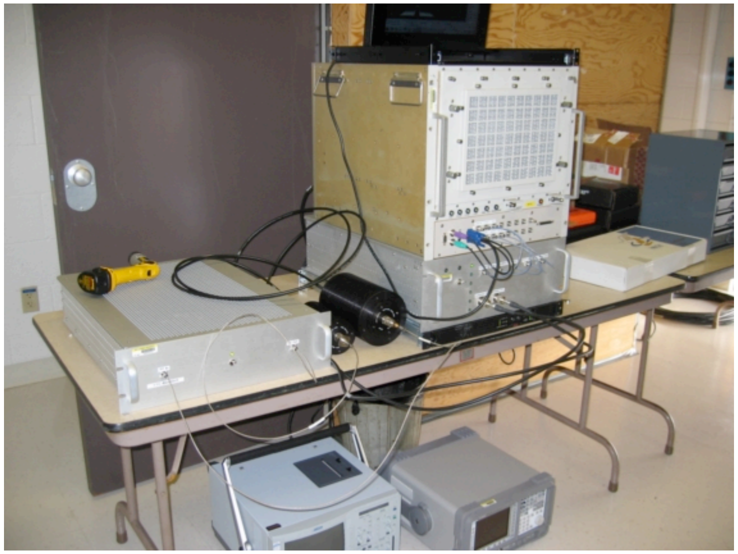
Technology Development: RF/Digital

- The RF subsystem module consists of five milled cavities that contain the two transmitter circuit boards, the two receiver circuit boards, and a timing distribution circuit board.

- A 9-bit, 480 MHz A/D is used to directly sample the received waveform. Both the DDS and the data acquisition module are housed within a single compact PCI card.

- The use of surface mounted RF components made it possible to fit the subsystem into a single slot of a compact PCI chassis.

- The PCI interface allows the system to stream data from the digital subsystem to the single board computer and to the hard drive at rates approaching 20 Mbytes/sec. This allows the system to operate at the required PRF of 700 Hz.



Cryospheric advanced sensor airborne radar

CAS radar system compact PCI modules

Mechanical Design

- Equipment has been designed for flight on a DHC-6 Series 300 Twin Otter aircraft
- Aluminum alloy support structure carries antenna and fairing
- Fairing generates up to 1000 pounds of lift; support structure is sized accordingly
- Electronics rack carries radar, GPS, and power equipment

Performance of FES System

Comparison of Instrument Parameter Requirements and Measurements

- The differences between the required instrument parameters and measured values are highlighted.
- The reduced transmitter power after filtering and switching losses is mitigated by the increased transmit pulse length and reduced receiver noise.
- The net performance gain is about 0.7 dB.
- The antenna is mounted on the side of a Twin Otter aircraft with its boresight at a 35 degree angle from the local nadir.

Instrument Parameters			
	Requirement	**Measured**	
Center Frequency	137	137	MHz
Bandwidth	20	20	MHz
Altitude	1	1	Km
Transmit Peak Power	**100**	**69**	**Watts**
Pulse Duration	**2.2**	**2.5**	**usec**
Transmit Waveform	CHIRP	CHIRP	
PRF	700	700	
Average Power Radiated	**0.150**	**0.120**	**Watts**
Antenna Radiation Gain	9.0	9.0	dB
Antenna Losses	2	2	dB
Antenna Width	1.1	1.1	Mtrs
Incidence Angle	30	30	Deg
Antenna Length	1.1	1.1	Mtrs
Filtering Losses	**1**	**0**	**dB**
Electronic Gain	70	70.3	dB
Receiver Noise Temperature	**1000.0**	**845.5**	**DegK**
A/D Saturation	-24	-24	dBW
A/D Bits	8	8	Bits
Velocity	46	46	Meter/sec
Sampling Rate (MSPS)	480	480	Msps
Cross Track Resolution	15.00	15.00	Meters
Along Track Resolution	15.00	15.00	Meters
Number of Looks	6	6	
Boresight Slant Range	1.15	1.15	Km

Performance of CAS System

Field Experimental System Link Budget

- The comparison of the Requirements vs the measured link budget tables shows that for a 2 meter thick sea ice layer, the SNR performance is degraded only by 0.4 dB compared to the original design.
- The parameter differences are highlighted in bold. The loss in transmitter peak power is almost completely made up by the increase in duty cycle and reduced receiver noise.

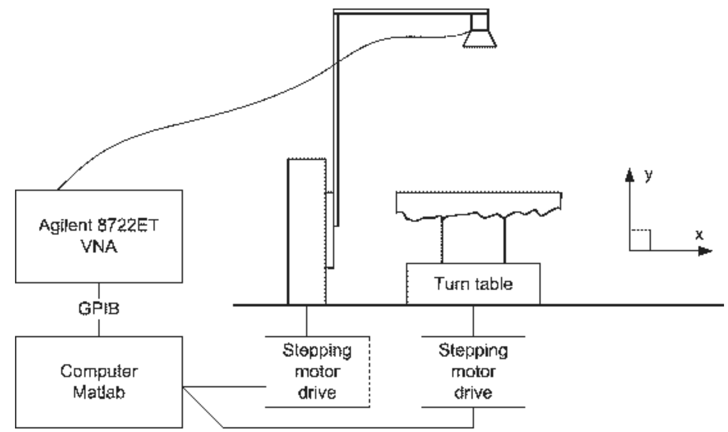
Parameter	Specified	Measured	Units
Transmit Power	**20.0**	**18.4**	dBW
Antenna Gain squared	17.9	17.9	dB
Antenna Losses squared	-4.0	-4.0	dB
Wavelength cubed	10.2	10.2	
Sigma Zero	-49.3	-49.3	dB
(1/4pi*Range^3)	-124.9	-124.9	
(Tc/(2LsinO))	27.8	28.3	
Received Power	**-102.2**	**-103.3**	**dBW**
Electronics Gain	70.0	70.0	dB
Power at A/D	-32.2	-33.3	dBW
Range Compression Ratio	16.4	17.0	
Range Defocusing	0.0	0.0	
Azimuth Compression	0.0	0.0	
Processor Filtering	0.0	0.0	
Power at Processor Output	-15.8	-16.3	dBW
Parameter (Noise)			
Receiver Noise	**-125.6**	**-126.3**	**dBW**
Electronic Gain	70.0	70.0	dB
Noise at A/D Input	-55.6	-56.3	dBW
A/D Converter Noise	-72.00	-72.00	dBW
Boresight Noise Eq Sigma Zero	**-72.7**	**-72.4**	**dB**
Boresight SNR at A/D input	**23.4**	**23.0**	**dB**

Controlled Laboratory Experiment

- A scaled frequency (millimeter wave) experimental set up was used to accommodate concept validation/ implementation in a laboratory environment.

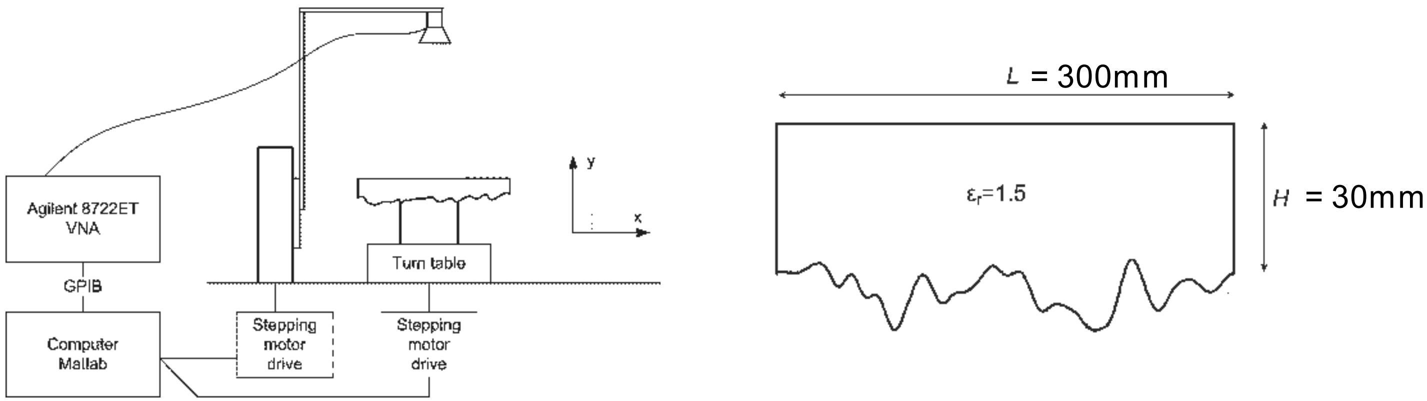
- In the experimental set up, a medium with random rough metallic surface on the bottom was placed on a turntable. Fixed incident and observation angles were employed, and the radar frequencies were varied.

- The metallic rough surface created rough surface scattering from the bottom surface in the backscatter direction.



Experiment setup

Controlled Laboratory Experiment



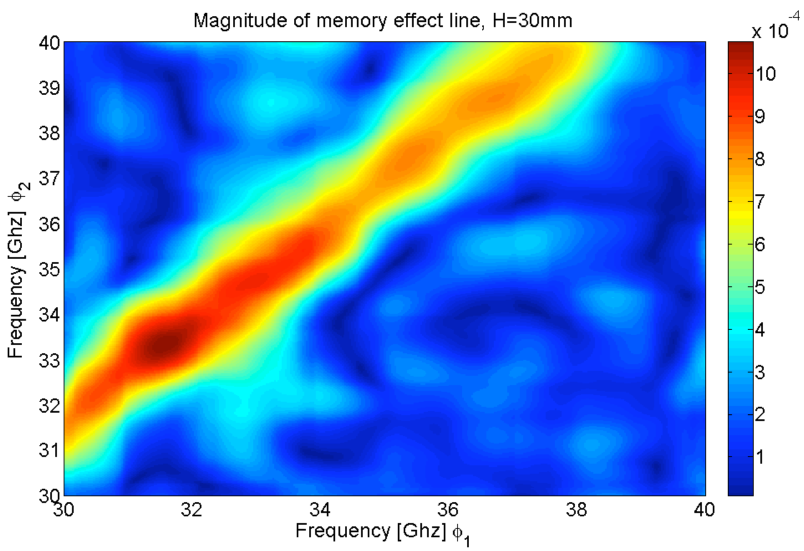
Left: experimental setup Right: medium characteristics

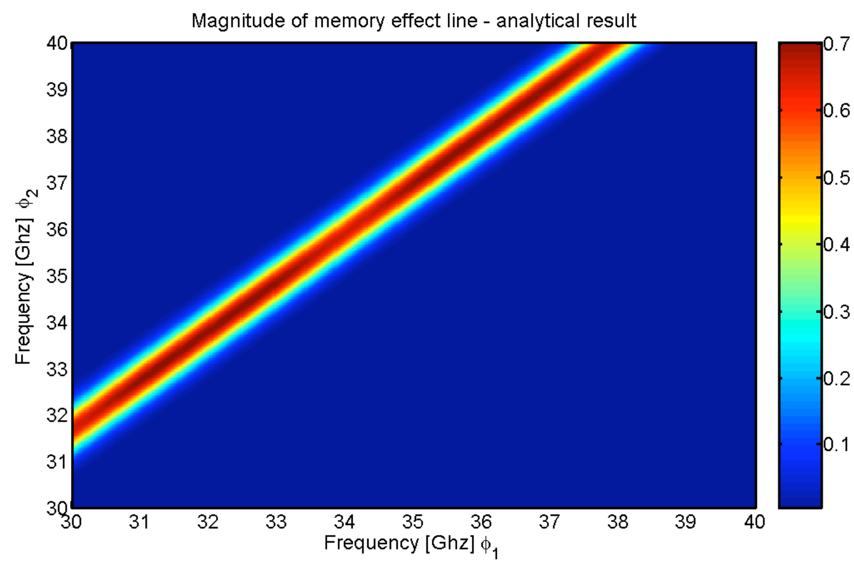
Parameters Used In The Experiments:

- Frequency: 30-40GHz with resolution of 25MHz
- Incidence Angles: 20 degrees and 19 degrees (We also have data for 20 and 18)
- Medium: dielectric constant = 1.5, mean thickness (H) = 30 mm, rms height = 3 mm, correlation length =12 mm, side length (L) = 300mm

Controlled Laboratory Experiment: Amplitude of ACF/FCF

• This experiment verified scattering response from a multi-layered medium as predicted by the analytical solution/demonstrate that the memory line occurs at the expected location.

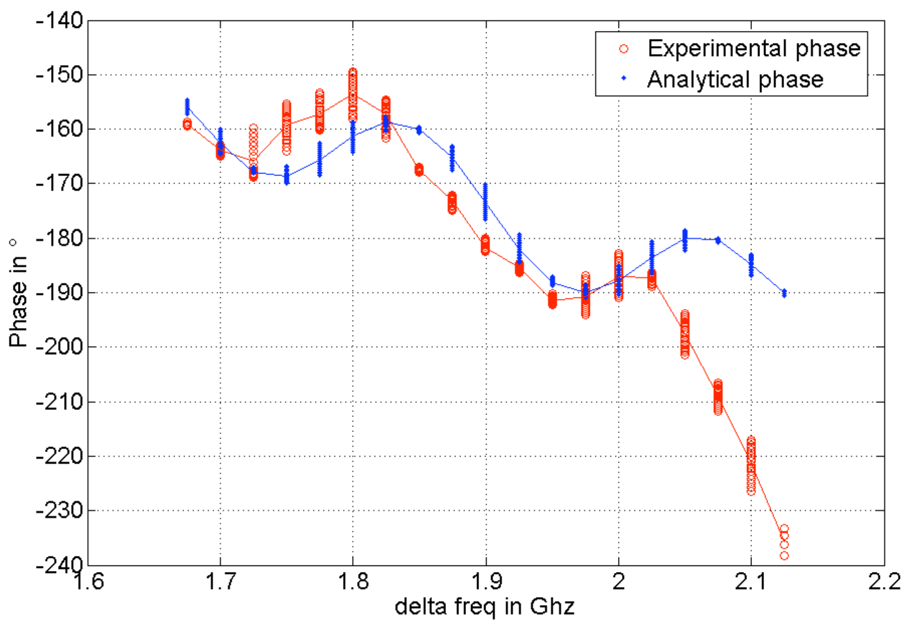


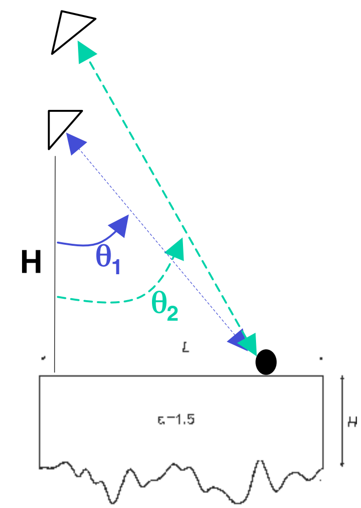


Memory line comparison. Left: experiment, Right: analytical solution

Controlled Laboratory Experiment: Phase of ACF/FCF

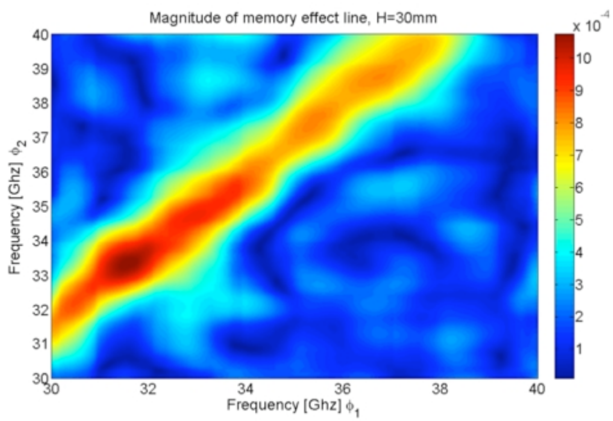
• Comparison of phase of correlation function between analytical solution and experimental data -→ calibration target required for calibration of backscattered data

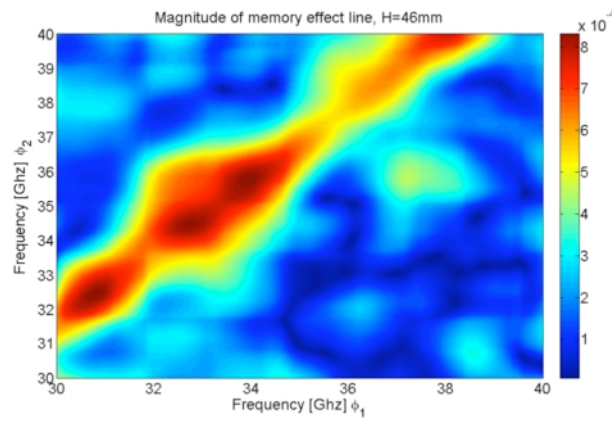




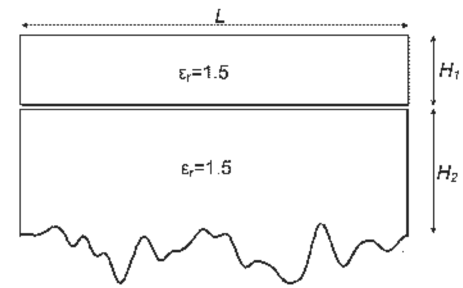
Controlled Laboratory Experiment: Thicker medium

Amplitude of Correlation Function
Left: thickness 30mm, Right: thickness= 46mm

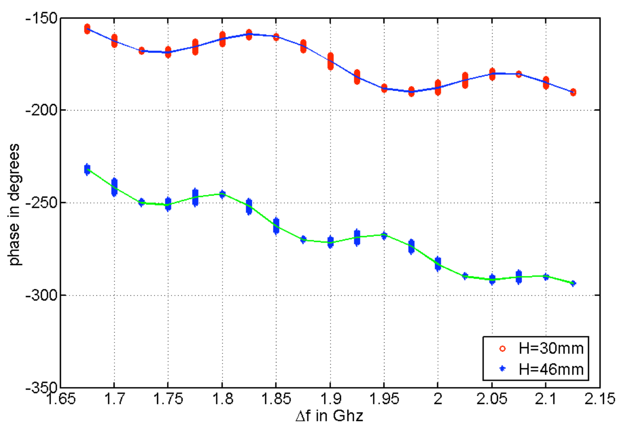


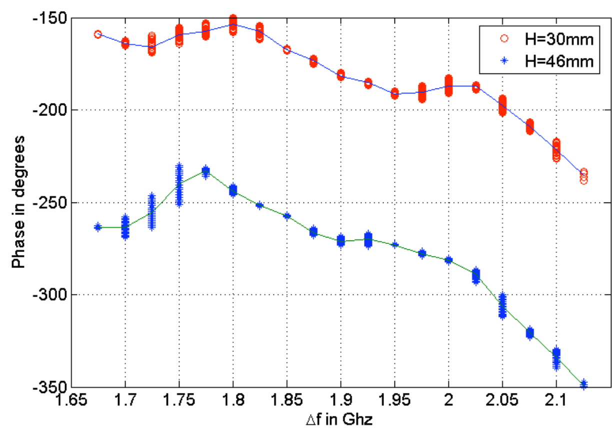


Setup for a different medium thickness



Phase of Correlation Function Comparison
Left: Analytical Solution, Right: Experimental data



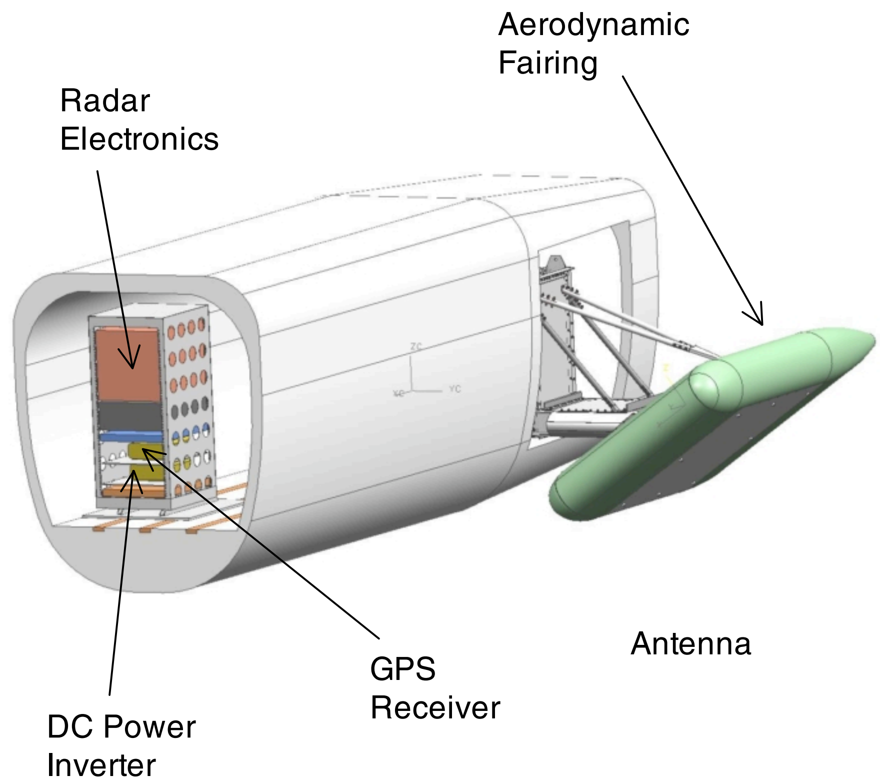


Summary

- We have developed the theoretical basis and prototype instrument technology for application of radar interferometry in the VHF band to the direct estimation of sea ice thickness

- Prototype VHF radar has been developed for operation on a Twin Otter aircraft for technology demonstration, and investigation of the ice thickness retrieval techniques.

- We anticipate that exercising the CAS prototype system over a variety of sea ice conditions will demonstrate the utility of CAS products for application to studies of climate and ocean circulation in the polar region.



Anticipated schedule: 2005
June: complete assembly
July: packing, shipping, and flight tests for FAA airworthiness certificate